



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Multiobjective Optimization in Combinatorial Wind Farms System Integration and Resistive SFCL Using Analytical Hierarchy Process

Moghadasi, Amirhasan; Sarwat, Arif; Guerrero, Josep M.

Published in:
Renewable Energy

DOI (link to publication from Publisher):
[10.1016/j.renene.2016.03.073](https://doi.org/10.1016/j.renene.2016.03.073)

Publication date:
2016

Document Version
Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Moghadasi, A., Sarwat, A., & Guerrero, J. M. (2016). Multiobjective Optimization in Combinatorial Wind Farms System Integration and Resistive SFCL Using Analytical Hierarchy Process. *Renewable Energy*, 94, 366–382. <https://doi.org/10.1016/j.renene.2016.03.073>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Multiobjective Optimization in Combinatorial Wind Farms System Integration and Resistive SFCL Using Analytical Hierarchy Process

Amirhasan Moghadasi, Arif Sarwat, Josep M. Guerrero^c

^{a,b} Energy Systems Research Laboratory, Florida International University, FL, USA

^c Department of Energy Technology, Aalborg University, Aalborg, Denmark

Corresponding Authors' Contact Information:

Amirhasan Moghadasi

Office: EC3920

Lab: EC 3920

Phone (Lab): 305 348 2935

Email: amogh004@fiu.edu

Mail: Florida International University (FIU)

10555 West Flagler St., EC3913

Miami, FL 33174

Multiobjective Optimization in Combinatorial Wind Farms System Integration and Resistive SFCL Using Analytical Hierarchy Process

Amirhasan Moghadasi, Arif Sarwat, Josep M. Guerrero

Abstract— This paper presents a positive approach for low voltage ride-through (LVRT) improvement of the permanent magnet synchronous generator (PMSG) based on a large wind power plant (WPP) of 50MW. The proposed method utilizes the conventional current control strategy to provide a reactive power requirement and retain the active power production during and after the fault for the grid codes compliance. Besides that, a resistive superconducting fault current limiter (RSFCL) as an additional self-healing support is applied outside the WPP to further increase the rated active power of the installation, thereby enhance the dc-link voltage smoothness, as well as the LVRT capability of the 50MW WPP. This is achieved by limiting the exceed fault current and diminishing the voltage dip level, leading to increase the voltage safety margin of the LVRT curve. Furthermore, the effect of the installed RSFCL on the extreme load reduction is effectively demonstrated. A large WPP has a complicated structure using several components, and the inclusion of RSFCL composes this layout more problematic for optimal performance of the system. Hence, the most-widely decision-making technique based on the analytic hierarchy process (AHP) is proposed for the optimal design of the combinatorial RSFCL and 50MW WPP to compute the three-dimensional alignment in Pareto front at the end of the optimization run. The numerical simulations verify effectiveness of the proposed approach, using the Pareto optimality concept.

Keywords—Low voltage ride-through, multi-objective optimization, superconducting fault current limiter, wind farm.

1. Introduction

Wind turbines with the grid connected mode of the operation play the significant role toward in sustainable energy development in the future. However, integration of large wind power plants (WPPs) can impose the adverse effects on the grid, particularly under abnormal grid voltage conditions [1]. Traditionally, wind turbine generators were tripped with circuit breakers once the voltage at their terminals reduced below 80% because the penetration level of the wind power was extremely small compared to the conventional generation systems and their impact on the grid was low. The trend towards integration of more WPPs has raised serious concerns about the stability of existing power networks, increasing the fault current levels and voltage reductions, thereby disconnecting a large wind farm. Recently, many power system operators in Europe and other parts of the world are expanding and modifying their interconnection requirements for wind farms through technical standards known as grid codes [2-4].

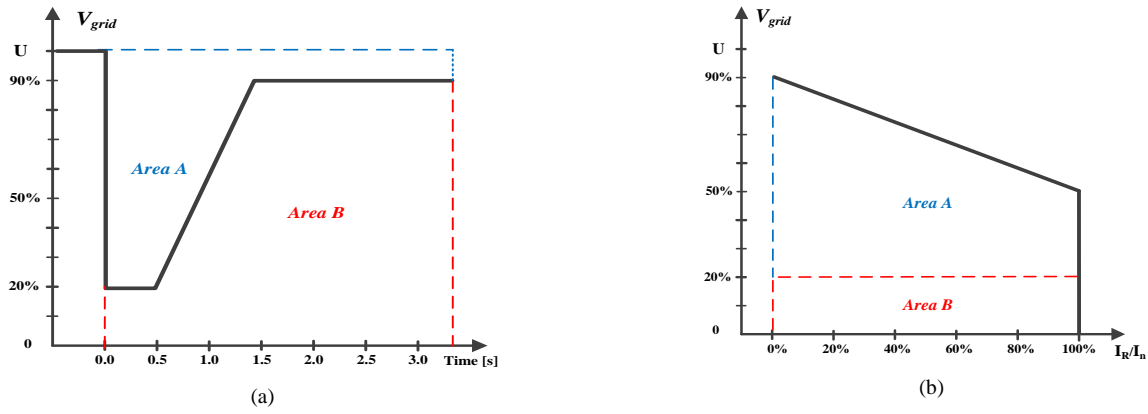


Fig 1. Danish grid codes. (a) LVRT requirement. (b) Reactive power support requirement

27

28 One of the critical demanding requirements, concerning the grid voltage support, is called low voltage ride-through (LVRT)
 29 capability, which is regularly being included in the new grid codes. Fig. 1(a) a shows practical example of the LVRT curve
 30 defined by the Danish system operator for wind turbines (WTs) connected to the grid. Based on this regulation, if the voltage
 31 remains at the level greater than 20% of nominal for a period less than 0.5 s, the WT should be connected to the grid. WTs are
 32 only stipulated to disconnect from the grid when the voltage profile falls into the Area B. Besides the LVRT requirements,
 33 some grid codes require large WTs to contribute to the voltage restoration of the power system by injecting the reactive power
 34 during the fault and the recovery period [3], while maintaining the operating point above the area of Fig. 1(b).

35 Permanent magnet synchronous generators (PMSGs) with a full-rating converter offers a number of advantages for WTs,
 36 including low maintenance requirements, more reactive power supply and better ride-through capability because power
 37 electronic converters are decoupled completely from the grid [5-7]. However, there is a strong interaction between the turbine
 38 control system and the mechanical loads the turbine experiences. The mechanical loads are divided into two distinct types:
 39 extreme and fatigue loads. Extreme loads are loads that a given component needs to be able to withstand once; while fatigue
 40 loads are accumulating over time and threaten to damage the turbine after several years of operation [8]. An important source
 41 of extreme loads may occur during fault events. At the beginning of the fault, the maximum power injected into the grid
 42 reduces proportional the voltage sag amplitude, while power injected from the wind generator remains relatively constant. Due
 43 to unbalance power between the mechanical-input power and the electrical-output power, the dc-link voltage as well as rotor
 44 speed exceeds their safety limits which can potentially force the wind turbine to disconnect from the grid. The quickly growing
 45 power ratings of the wind turbines simply exacerbate these problems. Thus, PMSG suffers from large variations of dc-link
 46 voltage during and after the grid fault and extreme loads occurring either prior or during the shut-down process [3, 8, 9]. Any
 47 control system that helps to avoid unnecessary faults or that improves the behavior during the shut-down process will reduce
 48 turbine loads or contribute to turbine availability.

Several studies have been proposed in the literature to limit the dc-link voltage variations and improve the LVRT capability of PMSG-based wind turbines [5-12]. Fast pitch control can help to reduce the input-mechanical power by rotating the blades about their longitudinal axis, also called pitching, and consequently curbs dc-link voltage fluctuations. In [13], a logical fast pitch controller along with fuzzy logic controller (FLC) for back to back converters has been proposed in order to enhance the transient performance of WTs during severe network disturbances. Another solution is to permit the excess wind energy to be temporarily stored in the turbine-generation shaft inertia during the grid faults [7, 11]. Although, techniques are the cheapest solutions for enhancing the LVRT capability of PMSG-based wind turbines, but these have a very slow dynamic response due to the mechanical constraints of the system, (the speed of the pitch actuator is slow to contribute alone to LVRT support). The most well-known method that is being used for the PMSG-based WT systems is the braking chopper (BC) with the low cost advantage and the simple control performance to consume this surplus power [14, 15]. However, in the large wind power plant, including many single wind turbines, the overall cost of using the BCs will be dramatically increased. Moreover, it is difficult to improve the power quality at the output of the wind turbine systems since the BC can just dissipate the power [6].

Various control methods are also proposed to ensure proper converter operation during fault conditions. The formerly analyzed converter control solutions [11, 17, 18], are based on the classical approach of using the linear proportional–integral (PI) regulators and pulsewidth/space vector modulation (PWM/SVM). The particular problem is that a linear PI controller is designed for normal network voltage levels, resulting in excessive currents at reduced voltage levels during the fault [10]. The nonlinear control methods are introduced to improve the classical current control method [19, 20], but most of these methods are complex and very sensitive to system parameters for practical applications, and need proper tuning of control [21].

This paper proposes an effective approach using resistive superconducting fault current limiter (RSFCL) as the additional support along with conventional converter control strategy based on PI regulators to further increase the rated active power of the installation, thereby enhancing dc-link voltage smoothness as well as the LVRT capability of the 50MW WPP. By using the RSFCL, the fault current is suppressed effectively and the voltage dip level of the WPP terminals is diminished, leading to enlarge the voltage safety margin of LVRT curve. Up to the present time, as far as the authors are aware, there has been no report on the RSFCL investigation in the large-scale of PMSG-based on WPP, which is the main motivation of this paper.

The first-cycle suppression of a fault current by a RSFCL can also reduce the activation of pitch angle control and can decrease the effect of the extreme loads on the turbine components. A RSFCL is considered as self-healing technology since it eliminates the need for any control action or human intervention due to its automatic excessive current detecting and automatic recovering from non-superconducting to superconducting states [23, 24]. These significant features of RSFCL can demonstrate that the proposed technique surpasses aforementioned methods using BCs and complicated nonlinear control system.

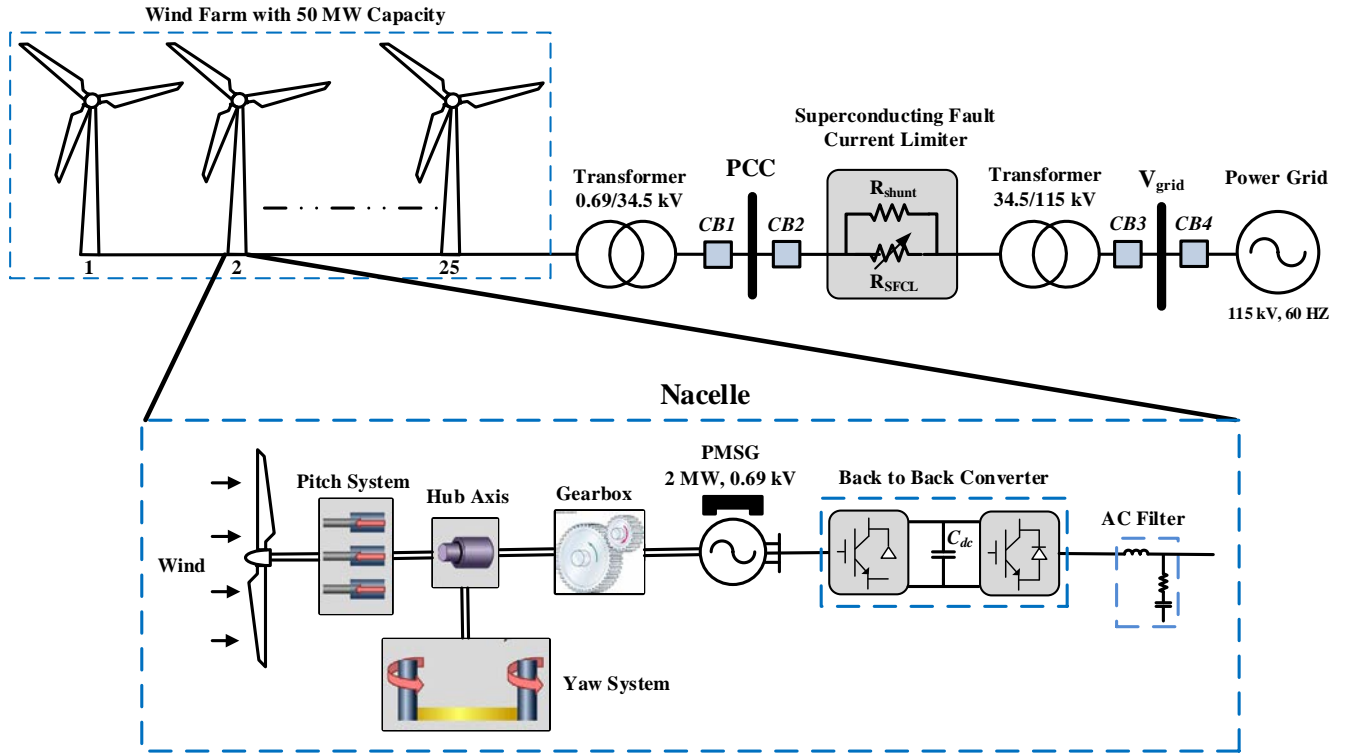


Fig. 2. Proposed combinatorial PMSG-based WPP and RSFCL.

However, a large WPP has a complicated structure using several components, and the inclusion of RSFCL composes this scheme more problematic for optimal performance of the system. Hence, the further effort in this paper is centralized on the most-widely decision-making technique based on the analytic hierarchy process (AHP) [25, 26], for the optimal performance of the combinatorial RSFCL and 50 MW WPP. The technique creates the Pareto optimality for simultaneously optimizing 3-D alignment that rarely reported the power system literatures. Effectiveness of the proposed approach, using the Pareto optimality concept is verified by the numerical simulations. The optimization technique figures out all the nondominated solutions on the Pareto front at the end of the optimization run.

2. Modeling of the PMSG-Based Wind Turbine

The structure of the proposed system including a 50-MW PMSG WPP and resistive SFCL is schematically shown in Fig. 2. The constituents of the wind turbine are aerodynamic, mechanical, and electrical parts. The generator are completely decoupled from the grid by power electronic converters (grid-side VSC and generator-side VSC which are connected back-to-back through the common dc-link capacitance). PMSG-based WTs may be represented as a combination of subsystems. The framework shown in Fig. 3 is typically used for modeling purposes, in which the relevant mathematical model has been cited in the several literatures [6, 7, 10,], and it is summarily considered here.

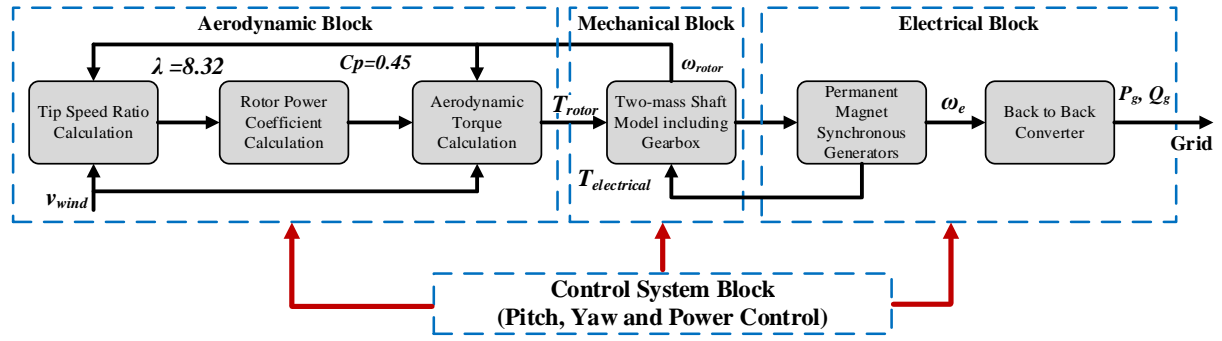


Fig. 3. Subsystems model used in PMSG-based wind turbine.

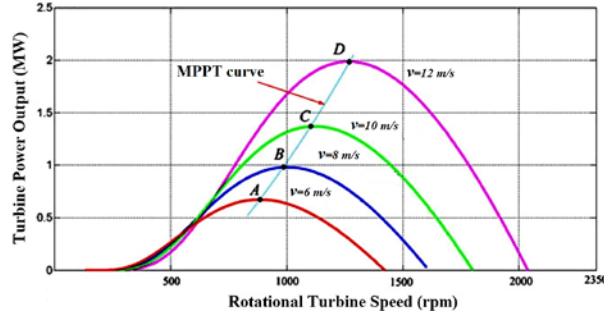


Fig. 4. Wind turbine characteristics.

2.1. Aerodynamic Model

According to the Betz theory, the aerodynamic power generated by the rotor is given by [6]

$$P_A = \frac{1}{2} \rho \pi R^2 v_{\text{wind}}^3 C_p(\lambda, \beta) \quad (1)$$

where ρ is the air density (kg/m^3), R is the radius of the blade (m), v_{wind} is the free-stream wind speed (m/s), and $C_p(\lambda, \beta)$ is the rotor power coefficient. In the PMSG-based WT, the obtained power depends on C_p , which is a function of both tip speed ratio (TSR) λ and blade pitch angle β , in which the TSR is defined as

$$\lambda = \frac{R \omega_{\text{rotor}}}{v_{\text{wind}}} \quad (2)$$

where ω_{rotor} is the rotational turbine speed. The numerical approximation of the power coefficient [27] is given by following non-linear equations

$$C_p(\lambda, \beta) = 0.73 \left(\frac{151}{\lambda_t} - 0.58\beta - 0.002\beta^{2.14} - 13.2 \right) e^{-\frac{18.4}{\lambda_t}} \quad (3)$$

$$\lambda_t = \frac{1}{\frac{1}{(\lambda - 0.02\beta)} - \frac{0.003}{(\beta^3 + 1)}} \quad (4)$$

In this paper, the optimal values of power coefficient ($C_{p\text{-opt}}$) and tip speed ratio (λ_{opt}) are 0.45 and 8.32, respectively.

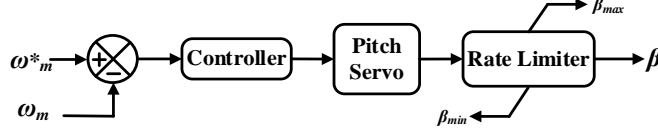


Fig. 5. Conventional pitch angle control used in FSIQ-based wind turbine.

$$P_{\max} = 0.5 \rho \pi R^2 \left(\frac{R \omega_{\text{rotor}}}{8.32} \right)^3 \times 0.45 \quad (5)$$

For an average wind speed of 12 m/s, which is used in this paper, the maximum turbine power output 2 MW and rotational speed 1200 rpm are obtained.

The aerodynamic of wind turbines is controlled by pitch control approaches, which have been developed for large WTs. The blades start to move around cut-in speed 4 m/s, and optimal aerodynamic efficiency is achieved at the wind speed rated about 12 m/s. The extra power obtained from wind speed between 4 and 12 m/s may be smoothly curtailed by spinning the blades using a pitch control to avoid overloading the wind turbine system. Fig. 5 depicts the conventional pitch angle regulator in which the input and output of the model are the rotational turbine speed ω_{rotor} and blade angle β , respectively.

The yaw system of a typical turbine is significantly slower than the pitch system and the structural dynamics. Since the yaw rates are so slow that there is very little interaction with the rest of the system behavior, it is often not considered at all. If yawing is to be considered it can be modeled similar to the pitch system but with significantly lower bandwidth and rate limits. The gearbox also plays an essential role in the WTs to adapt low-speed, high-torque rotation of the turbine rotor into the faster rotation of the electrical generator. The critical issue in implementing the gearbox technology is the extreme loads, which may lead to misalignment of the drive train and a gradual failure of the gear components, consequently increasing the capital and operating cost of the WTs.

2.2. PMSG Model

Based on the reference frame theory [6, 11], stator voltage equations in a d-q synchronous frame are modeled:

$$v_{sd} = R_s i_{sd} + L_s \frac{d}{dt} i_{sd} - \omega_e L_d i_{sq} \quad (6)$$

$$v_{sq} = R_s i_{sq} + L_s \frac{d}{dt} i_{sq} + \omega_e L_q i_{sd} + \omega_e \psi_r$$

(7)

where v_{sd} and v_{sq} are the d- and q-axes stator voltages, i_{sd} and i_{sq} are the d- and q-axes stator currents, R_s and L_s are the stator resistance and inductance, L_d and L_q are the d- and q-axes inductance, ψ_r is the rotor flux, and ω_e is the electrical angular speed. For the generator with surface-mounted permanent magnets, d- and q-axes inductances are the equal ($L_d = L_q$), resulting a simple interpretation of the electromagnetic torque $T_{electrical}$ and aerodynamic torque on the rotor T_{rotor} expressed as

$$T_{electrical} = \frac{3}{2} p \psi_r i_{sq} \quad (8)$$

$$T_{rotor} - T_{electrical} = J \frac{d}{dt} \omega_{rotor} + b \omega_{rotor} \quad (9)$$

where p is the number of machine pole pairs, J is moment of inertia for turbine-generator, ω_m is shaft mechanical speed, and b is friction coefficient.

3. Power Control Strategy

Detail of the proposed power control scheme for the PMSG based on the full-power converter topology is illustrated in Fig. 6. As it can be seen, it is schematically divided into two main blocks. On the one hand, controlling the active and reactive power of the PMSG is obtained via a generator-side VSC. On the other hand, the management of the active and reactive power released to the grid by the PMSG along with the dc-link regulation is accomplished via the grid-side VSC. The active and reactive power references to be injected by the grid-side VSC are obtained, so that the whole wind farm can fulfill the grid code requirements.

3.1. Generator-Side VSC Control

The control block diagram of generator-side VSC is shown in Fig. 6(a), which is based on stator voltage equations (6) and (7) obtained in d-q synchronous frame. Several maximum power point tracking (MPPT) algorithms have been reported for the PMSG-based WT [28-30]. The outcome of the MPPT unit provides the reference value of the rotational turbine speed (ω_{rotor}^*) for the generator-side VSC controller. This paper mainly focuses on the converter control, and hence, the MPPT control method was not discussed. The speed reference ω_m^* is acquired by a MPPT method mentioned in (5) in order to extract the maximum amount of power with the actual wind force, while the rotational speed error is given as the input to a PI controller in order to generate the q-axis stator current command (i_{sq}^*). Also, the reactive power produced by the wind turbine is regulated at zero ($i_{sd}^*=0$) for unity power factor operation. The error between the reference dq-axis currents and the actual dq-axis currents, i_{sd} , i_{sq} are used as inputs to the linear PI controllers to produce dq-axis voltage commands, v_{sd}^* , v_{sq}^* after the decoupling. The angle θ_e calculated from the rotational speed of the PMSG is applied in a park transformation to engender gate signals using the carrier wave of pulse width modulation (PWM) operation.

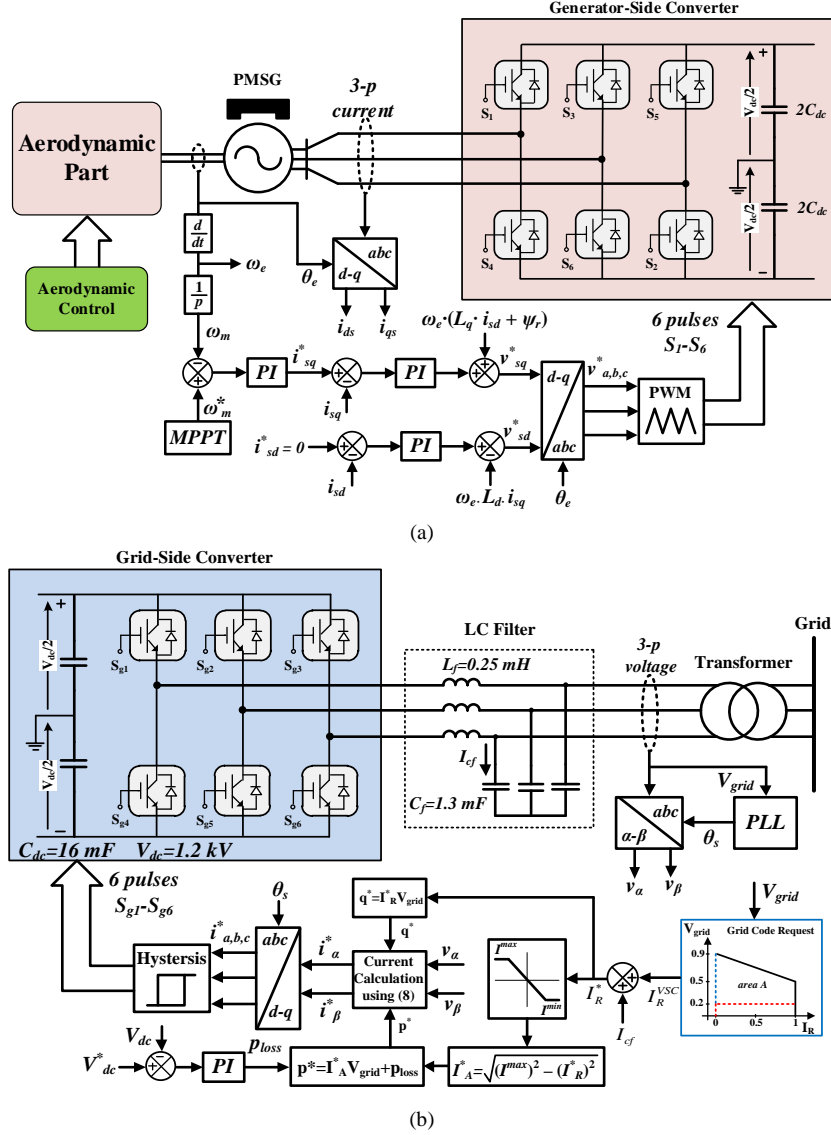


Fig. 6. Proposed power control strategy for WPP. (a) Control block diagram of the generator-side VSC. (b) Control block diagram of the grid-side VSC.

3.2. Grid-Side VSC Control

The proposed grid-side converter controller is provided in Fig. 6(b) to calculate the current references to be inserted by the grid-side VSC in order to fulfill the grid code requirements. Further, this controller preserves the dc-link capacitor voltage at the set value 1.2 kV, which assures the active power swapping from the PMSG to the grid. In the steady state condition, the maximum capacity of current, I_{max} is used to produce 2 MW active power ($I_R^{VSC} = 0$). In the next stage, p^* , which is added to the PI controller from the dc-link voltage regulator, and q^* transformed into the instantaneous power α - β method based on α - β -0 reference frame [23]. It has been mathematically formulated as

$$\begin{bmatrix} I_{\alpha}^* \\ I_{\beta}^* \end{bmatrix} = \frac{1}{v_{\alpha}^2 + v_{\beta}^2} \begin{bmatrix} v_{\alpha} & -v_{\beta} \\ v_{\beta} & v_{\alpha} \end{bmatrix} \begin{bmatrix} p^* + p_{loss} \\ q^* \end{bmatrix} \quad (10)$$

183

184 The angle θ_s for the Park transformation is detected from the three-phase voltages at the low-voltage side of the grid
 185 transformer by using a phase-locked loop (PLL). Finally, gate signals are generated for grid side VSC switches using the
 186 Hysteresis module [31], shown in Fig. 6(b). Under a grid voltage dip, the reactive current, I_R^{VSC} in proportion to the voltage
 187 reduction should be provided during the fault in order to meet the LVRT requirement according to the characteristic shown in
 188 Fig. 1(b).

189 Injection of reactive power has the highest priority in area A, but free capacity of current, I_A^* must also be utilized to retain the
 190 active power production related to the voltage sag magnitude, while the generator continues to provide active power at nominal
 191 value. In this case, the dc-link voltage exceeds its safety limits, leading a system malfunction or even a component failure.
 192 However, the rapidly rising the dc-link voltage, under a system fault, is difficult to be avoided by only using the PI controller.
 193 For this reason, this paper proposes a RSFCL used in outside of the wind farm, as shown in Fig. 2. The RSFCL makes it
 194 possible to suppress the dc-link voltage fluctuations by limiting the magnitude of the fault current, thereby increasing the
 195 output active power capacity and improving the LVRT capability of the wind farm. A further analysis is accomplished in
 196 Section 5.

197 **4. Electro-Thermal Modeling of a RSFCL**

198 The resistive superconducting fault current limiters (RSFCLs) have been launched and introduced into the network as a self-
 199 healing technology to curb prospective fault currents immediately to a manageable level by suddenly raising the resistance
 200 value [22, 23]. Furthermore, after the fault current is profitably repressed, the RSFCL can be restored to the primary state
 201 without additional aid. RSFCL has a simple structure with a lengthy superconductor wire inserted in series with the
 202 transmission lines. With the recent breakthrough of second-generation high-temperature superconductor (HTS) wires, the
 203 SFCL has become more viable [26]. Considering the superconducting material, BSCC-2223 is the conductor, which has
 204 commonly been utilized for most of the tentative RSFCLs [32, 33].

205 To preserve the superconductor from detrimental hot spots during the operation, the shunt resistance, R_{shunt} is essential. This
 206 parallel resistance must be contacted all over the length of the superconductor, and it regulates the controlled current to elude
 207 over-voltages likely occurring when the resistance of the superconductor increases much quicker. The current limiting behavior
 208 of the RSFCL can be modeled by the resistance transition of HTS tapes in terms of the temperature and the current density, as
 209 defined by the following equation [23]

$$R_{SFCL} = \begin{cases} 0, & \text{if } i_{sc} < I_c \text{ and } T < T_c \\ \text{if } i_{sc} > I_c, T < T_c \\ \rho_f \frac{V_{sc}}{A_{sc}^2} \left\{ \frac{J_{c0}}{|J|} \left(\frac{T-T_c}{T_c-T_b} \right) + 1 \right\} \\ \rho_n \frac{V_{sc}}{A_{sc}^2} \left(\frac{T}{T_c} \right), & \text{if } T > T_c \end{cases}$$

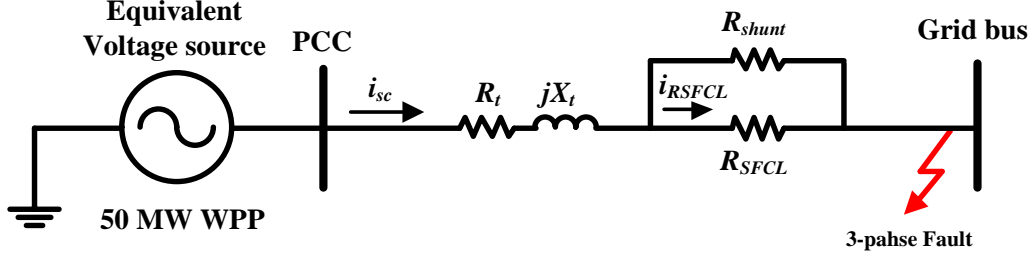


Fig. 7. Equivalent circuit of proposed system in fault condition.

where T_c , T_b , J_{c0} , V_{sc} , and A_{sc} are critical temperature, liquid nitrogen temperature, critical current density, superconductor volume, and cross section, respectively. Also, i_{sc} , I_c , ρ_f , and ρ_n are short-circuit current, critical current, flux flow resistivity, and normal resistivity, respectively. In this description (9), three possible states for superconductor are; 1) the flux-creep state at a temperature and a current under the critical rate; 2) the flux flow state at a current over the critical value, but a temperature under the critical rate; and 3) the normal conductive state at a temperature higher the critical amount.

According to the equivalent circuit of the proposed combination, shown in Fig. 7, if the asymmetrical component of the fault current is ignored, the short-circuit current through the RSFCL branch can be stated by the following equations

$$i_{RSFCL}(t) = \frac{R_{shunt}}{R_{SFCL} + R_{shunt}} \times \frac{V_m}{\sqrt{R^2 + (L_T \omega)^2}} \sin(\omega t) \quad (12)$$

where $R = R_{trans} + R_{shunt} \parallel R_{SFCL}$, L_T is the inductance of the transformer, and V_m is the magnitude low voltage side of interfacing transformer. The total fault energy dissipated in the HTS tapes, Q_{sc} is calculated using (13), where Δt_{sc} is the duration of the fault [34].

$$Q_{sc-3ph} = 3 \int_{\Delta t_{sc}} R_{SFCL} i_{RSFCL}^2(t) dt \quad (13)$$

Substituting (12) into (13) gives the following

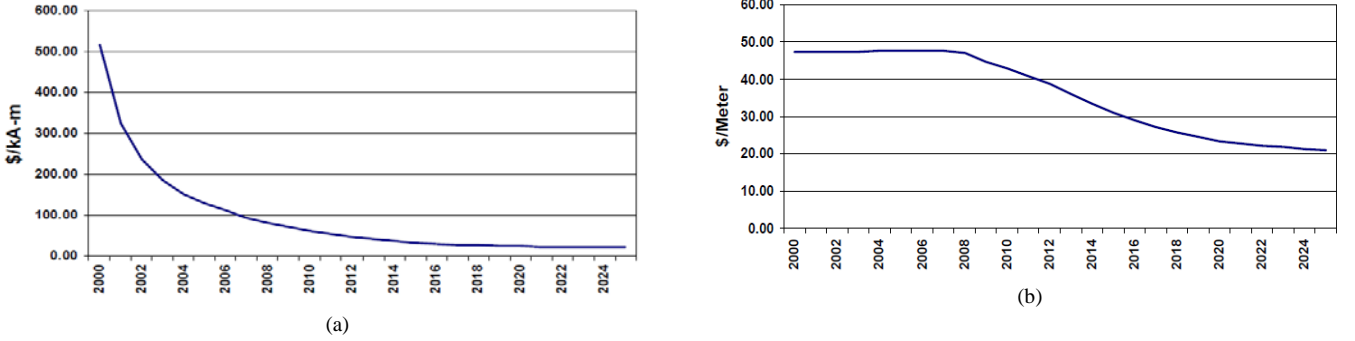
$$Q_{sc-3ph} = \frac{3V_m^2 R_{SFCL}}{R^2 + (L_T \omega)^2} \left[\frac{\Delta t_{sc}}{2} - \frac{\sin(2\omega \Delta t_{sc})}{4\omega} \right] \quad (14)$$

229 The RSFCL model should be a reasonable approximation of transient SFCL behavior during faults and, therefore, should
 230 consider thermal properties. The thermal model of RSFCL has been generically estimated as follows [24]

$$231 \quad T(t) = T_0 + \frac{1}{C_{sc}} \int_0^t [Q_{sc}(t) - P_{cool}(t)] dt \quad (15)$$

232 where T_0 is ambient temperature, C_{sc} is the heat capacity of the superconductor, and P_{cool} is the power cooling.

233



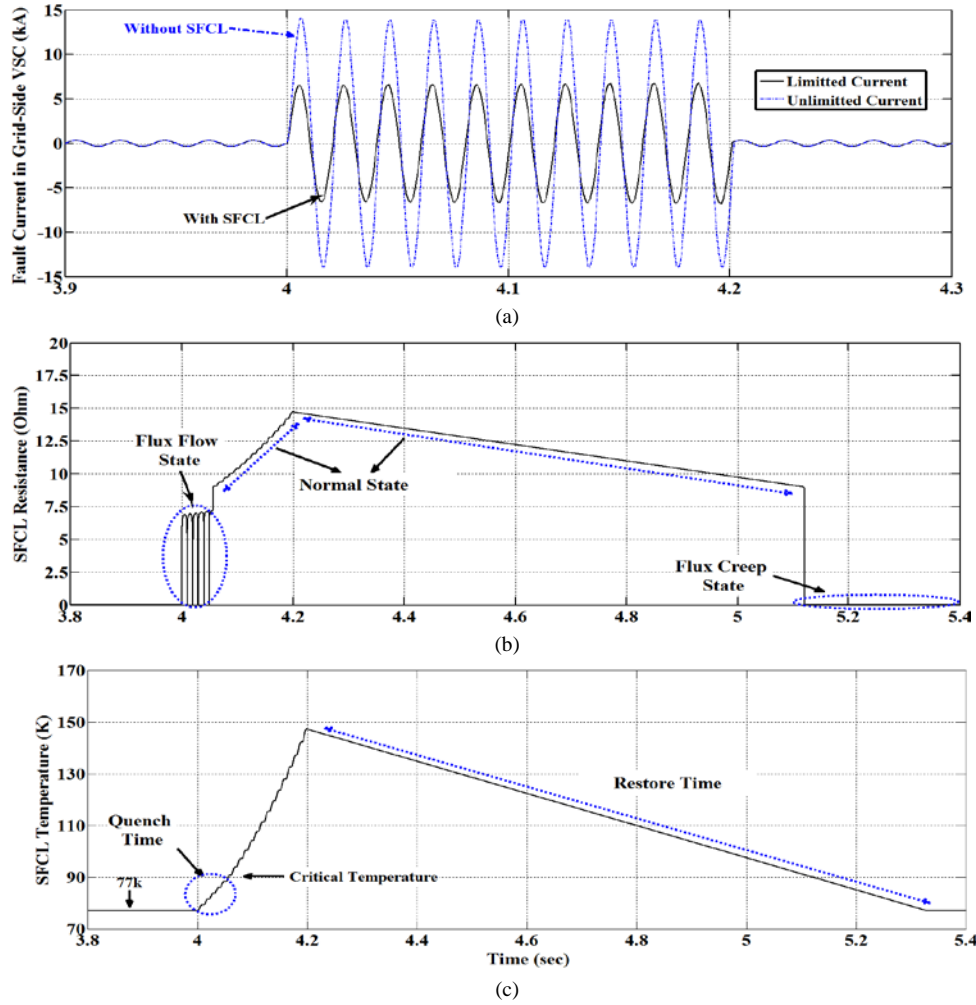
234 Fig 8. HTS wire cost [35]. (a) Dollar per Kiloamp per Meter. (b) Dollar per Meter.

235 4.1 Economic Feasibility of the RSFCL

236 Several main factors affect for determining the actual size and the cost of a resistive SFCL, such as the length of applied
 237 superconducting wire, the cooling machinery, the geometry of RSFCL module, and the rated power and voltage system, where
 238 RSFCL must be installed. Practically, the whole superconducting length is used in form of helix to shape the superconducting
 239 tube. In reality, several tubes may be connected in parallel to achieve a particular resistance in form of cylindrical geometry.
 240 The rough estimation for the RSFCL size can be achieved based on design details of the RSFCL projects in the worldwide
 241 [35]. Accordingly in this paper, the RSFCL module installed in the transmission system with voltage rate of 34.5 kV and power
 242 rate of 50 MVA would be much less than 4 m in both diameter and height.

243 After recent progress of the economical second-generation HTS wires, SFCLs are becoming more practicable, due to low
 244 manufacturing costs, low ac losses, higher current densities, and better operational performances, and is eventually expected to
 245 be at least a factor of ten lower in the cost than the presently available HTS conductor [36]. The cost of HTS wire is generally
 246 described by two parameters: the maximum amount of current that the HTS wire can conduct; and the manufacturing cost per
 247 meter of wire. Fig. 8 illustrates how the HTS wire cost of RSFCL is expected to decrease over the next two decades as
 248 production increases. The impact of cooling system on the future competitiveness of the RSFCL devices is critical. The 1999
 249 benchmark cost of a medium-sized cryogenic refrigeration unit was about \$60,000/kW_{cold} at 77K. Economies of scale typical
 250 of the cooling refrigeration industry were applied to represent the expected decline in refrigeration costs. This declining cost

268 solver with a $5 \mu\text{s}$ step size. A three-phase symmetrical grid fault is considered, since the fault ride-through capability of the
 269 regional grid codes mostly refer to this type of fault. Thus, a three-phase fault is applied in the middle of the transmission line
 270 at $t = 4 \text{ s}$ and is cleared after 200 ms, resulting in a 70% depth of the voltage dip at the PCC. To assess the damping behavior of
 271 the RSFCL, simulations are carried out for without and with the presence of the RSFCL. The expediency of the RSFCL
 272 component for managing the fault current, as well as resistance and temperature variations of the RSFCL is demonstrated in
 273 Fig. 10. The peak current for phase a in the pre-fault value is 850 A and then exceeds 14.2 kA without connecting RSFCL,
 274 whereas with the RSFCL incorporated on the main road of the wind farm, the fault current is limited effectively to reach about
 275 5.1 kA (see Fig. 10(a)).



280 Fig. 10. RSFCL model response. (a) Fault current waveform without and with RSFCL in a single-phase system. (b) Resistance variation in flux flow and
 281 normal state. (c) Temperature rise.

284 Fig. 10(b) illustrates the limiting resistance of the RSFCL, which went up to 7.1Ω in the flux flow state and rise to reach a
 285 normal stat value of 15Ω after ten cycles of the fault. A retrieval of the Fig 10(b) and (c) will determine, when a fault takes
 286 place at $t = 4\text{s}$, the quench time (a transition from a superconducting mode to a resistive mode) is initiated by going through the

flux-flow state during of 0.1s and then to the normal state at a temperature rise of 90° K (critical temperature for HTS tap). Fig. 11(a) shows the voltage profile at the PCC in the proposed integration system during a three-phase short circuit. In the absence of the reactive injection and RSFCL, the voltage reduction of 70% occurs. In this case, the voltage at the PCC cannot be restored to the nominal value because of an instability issue on the proposed system and the WPP must be disconnected from the grid. With the adoption of the reactive injection control, the voltage dip is decreased, reaching 50% before recovering immediately to the nominal value upon clearing the fault. Based on the reactive power support requirement (Fig. 1(b)), for a 50% voltage reduction, all the capacity of the wind farm is occupied by reactive power.

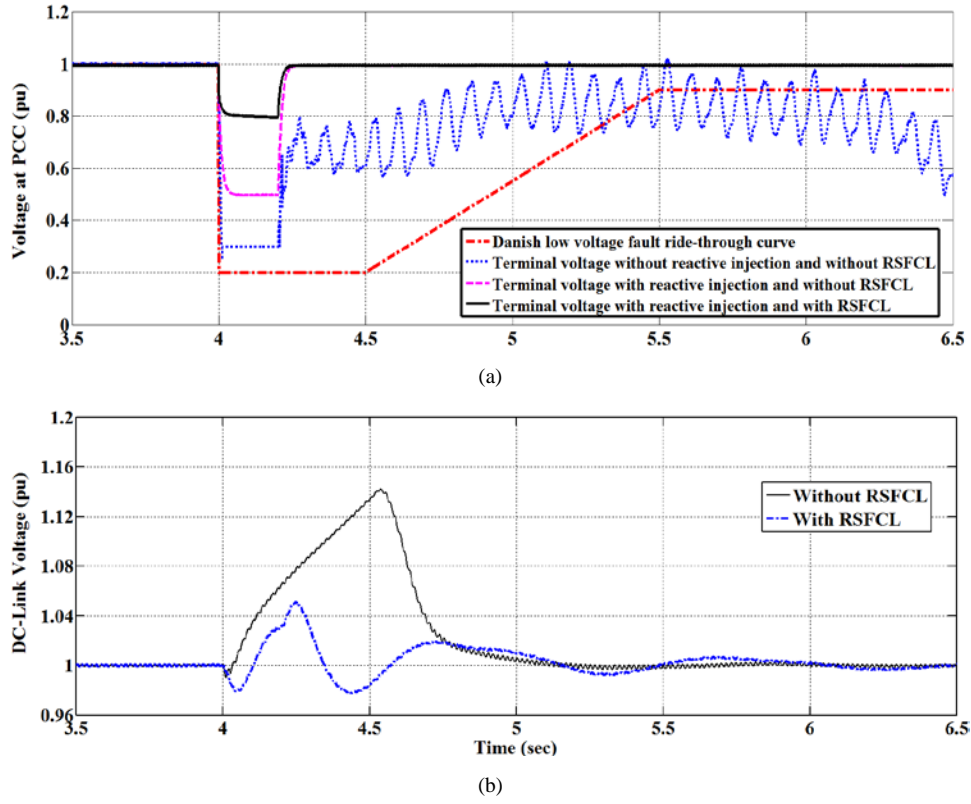


Fig. 11. Operation of the proposed combinatorial WPP and RSFCL during and after fault (a) Voltage profile at wind farm terminal (b) dc-link voltage with and without RSFCL.

As can be observed in Fig. 12(b), the reactive power injected during the fault (without RSFCL) allows the wind farm to satisfy the specifications of grid code requirements such as increasing the LVRT capacity. However, due to the lack of output active power in the grid-side VSC and consequently the earlier-mentioned unbalanced power during the fault, the dc-link voltage is significantly increased to about 1.14 pu, where a regular reactive power control with no RSFCL is used i.e., 14.58 % over voltage (Fig. 11(b)). This effort proposes the RSFCL as an additional supporting method besides the reactive power control to improve the LVRT capability and smoothen the dc-link voltage of the wind farm. This method increases the voltage stability

margin with respect to the LVRT curve as shown in Fig. 11(a), in which using the RSFCL significantly reduces the magnitude of the voltage sag to around 20%. In addition, the peak value of the dc-link voltage transient is reduced when using the RSFCL, evident by its decline it to 1.05 p.u (less than 5% over voltage), as shown in Fig. 11(b). Fig. 12(a) illustrates the active power output of the wind farm with and without the RSFCL, in which it is considerably kept at rated value of 50 MW before occurring the fault. After installing RSFCL, the drop in the active power decreased from 0 MW to 35 MW and back to the normal operation gradually as the fault is cleared. That is, the presence of the RSFCL increases the retaining of the active power production for the PMSG-WPP by approximately 60%, during the fault condition.

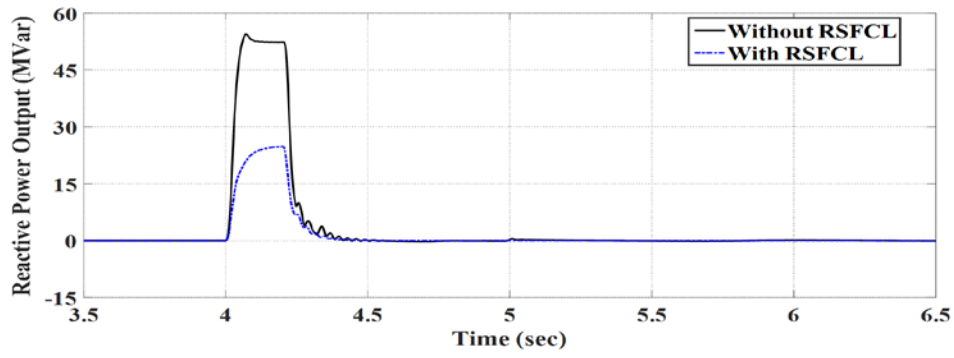
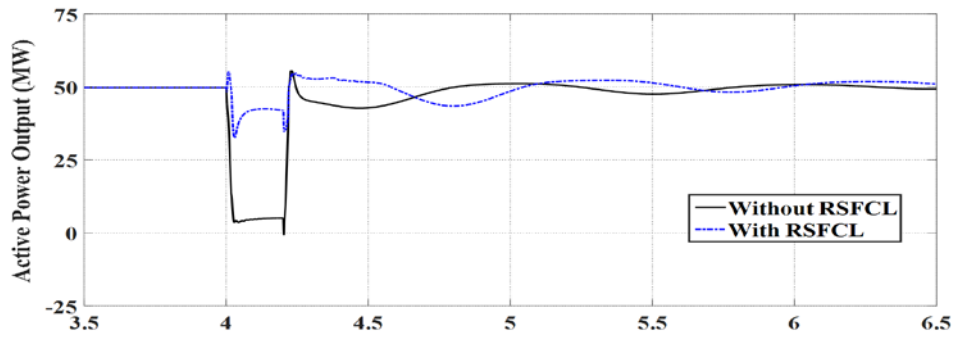
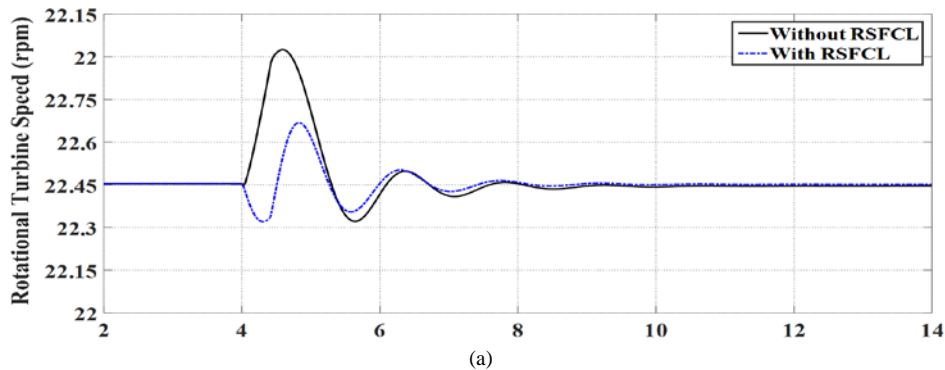


Fig. 12. Operation of the proposed combinatorial WPP and RSFCL during and after fault (a) Active and reactive power at the PCC without the RSFCL. (b) Active and reactive power at the PCC with the RSFCL.



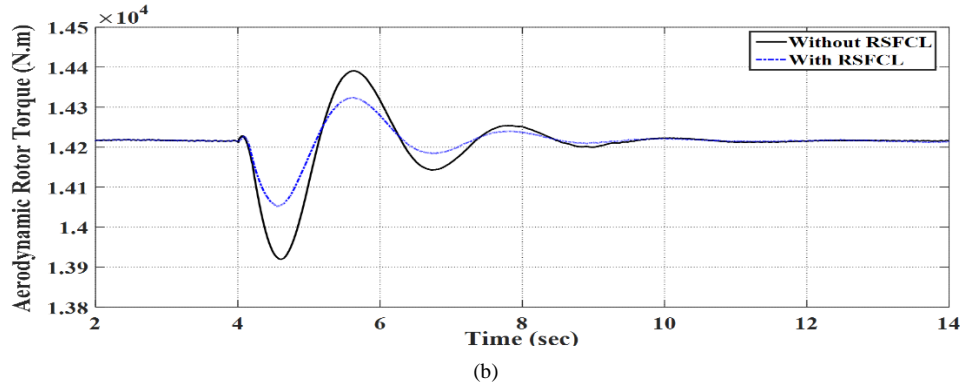


Fig. 13. Dynamic performance of the turbine side with and without applying the RSFCL. (a) Rotational turbine speed. (b) Aerodynamic rotor torque.

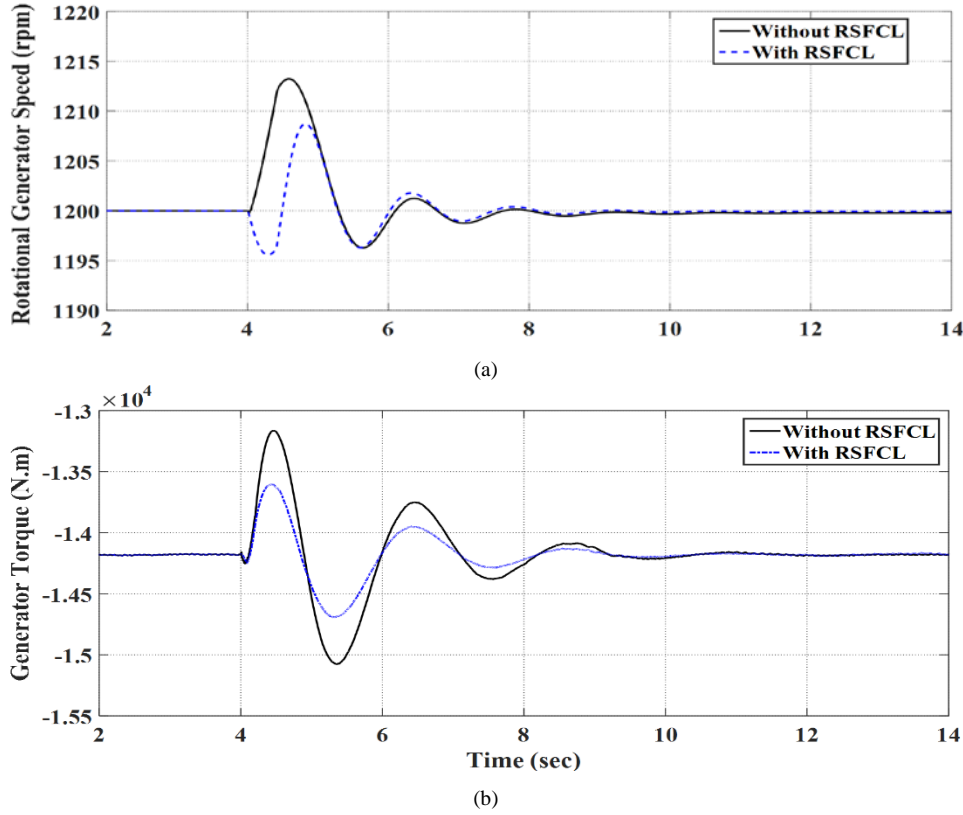
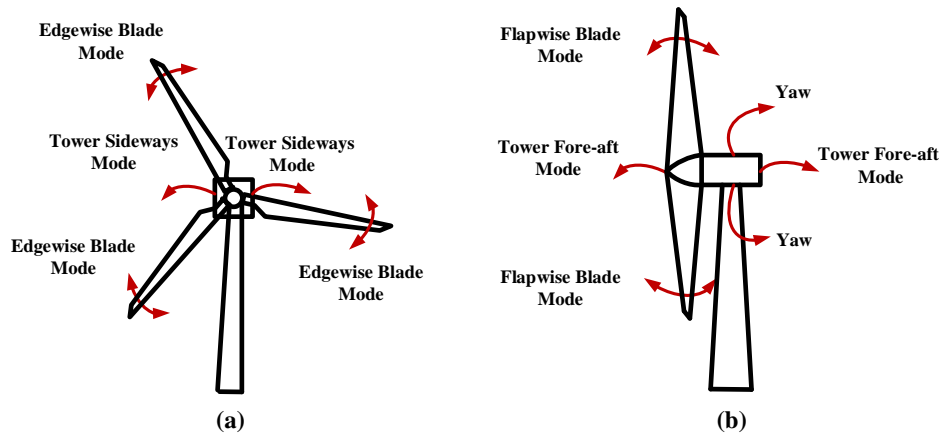


Fig. 14. Dynamic performance of the generator side with and without applying the RSFCL. (a) Rotational generator speed. (b) Generator torque.

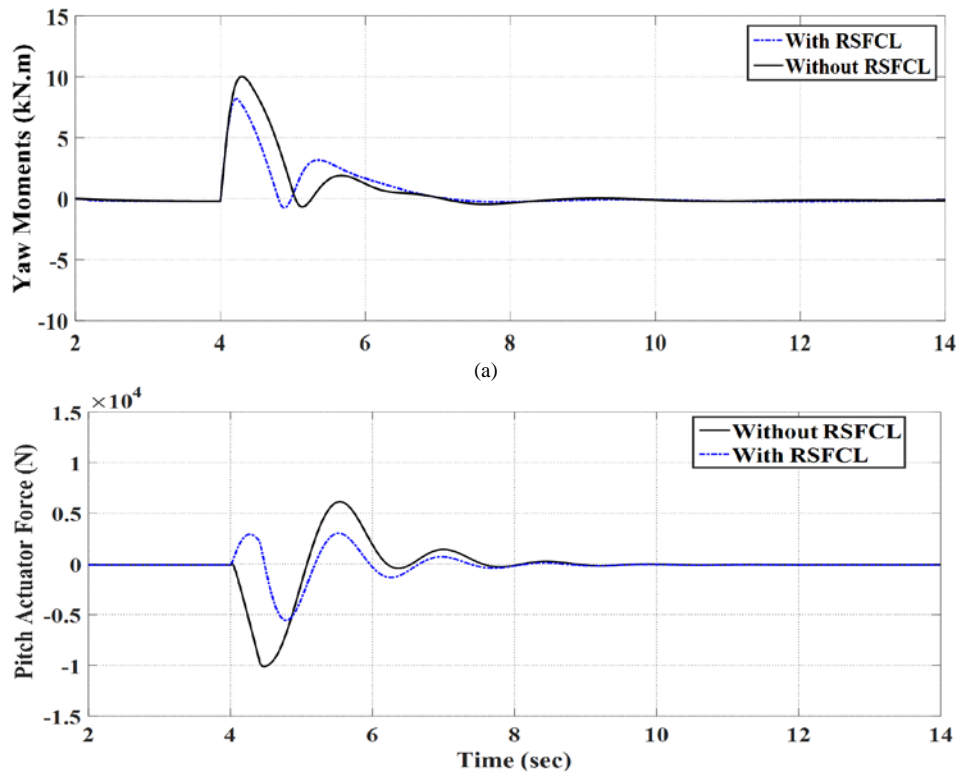
5.1 Effect of RSFCL on Extreme Load Reduction on WT Structure

In order to analyze the impact of the RSFCL on WT extreme loads, a combination of the FAST model and SimPowerSystems can accurately simulate detailed aerodynamics and mechanical aspects of the wind turbine. In this study, it is assumed that wind speed at the hub remains constant at 12 m/s. Rotational speed and mechanical torque responses of the rotor turbine and generator are shown in Fig. 13 and Fig. 14, respectively. As it can be seen, the rotational speeds and mechanical torque increase during the fault period, which may lead to power system instability and is detrimental for the turbine generator system if the fault duration is long and proper auxiliary devices are not used (no controller). However, RSFCL can limit the rate of

337 rising of machine speed and the aerodynamic torque imposed on rotor/shaft in order to make better stability.
 338 In this work, a number of the degrees of freedom available in the simulation model are used for analysis of the extreme loads,
 339 including tower fore-aft and sideways modes, tower yaw mode, and blade flap wise and edgewise modes. All these modes are
 340 depicted in Fig. 15, which contains illustrations of a wind turbine seen from the front and side views. The failure at the system
 341 causes extreme loads on structural parts of the WTs. Figs. 16-18 show the simulation results of several key loadings, such as
 342 hub loadings, blade root loadings, and tower base loadings, of the proposed WPP, which are compared without and with the
 343 presence of the RSFCL.



344
 345 Fig. 15. Wind turbine structure. (a) Wind turbine from the front, illustrating sideways and blade edgewise modes. (b) Wind turbine from the side, illustrating
 346 fore-aft, blade flapwise, and yaw modes.



347
 348

349

(b)
Fig. 16. Dynamic performance of the WT under the extreme load with and without the RSFCL. (a) Yaw moments. (b) Pitch Actuator Force.

Fig. 16 depicts hub loadings, including the pitch actuator force and yaw moments, during the three-phase fault. The impact of the installed RSFCL on yaw moments is effectively demonstrated by 20% reduction in the magnitude of the value during the fault in proportion to the case with no using RSFCL, as shown in Fig. 16(a). With the onset of the fault, the pitch actuator force first shows a dip then a rise, and then it reduces to a negative value and finally increases to zero and becomes constant. Rise in the pitch actuator force after it reached negative value is due to large inertia of the rotor. However, application of RSFCL shows a promising solution for reducing the fluctuation of the pitch actuator force, as illustrated in Fig. 16(b).

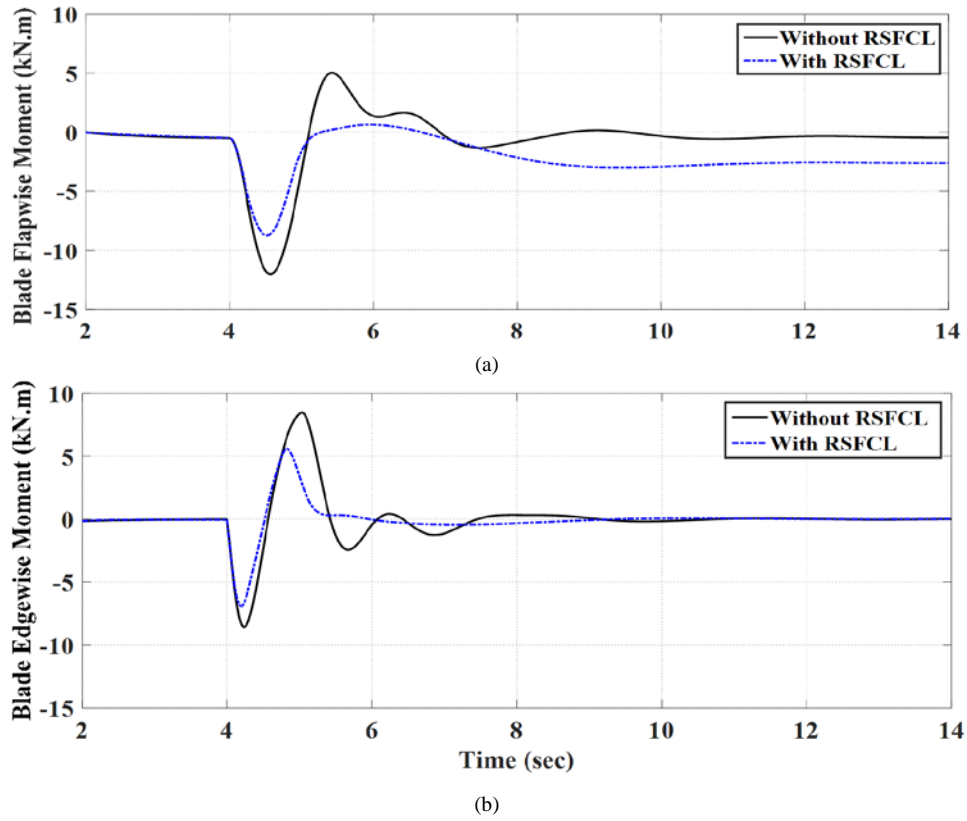
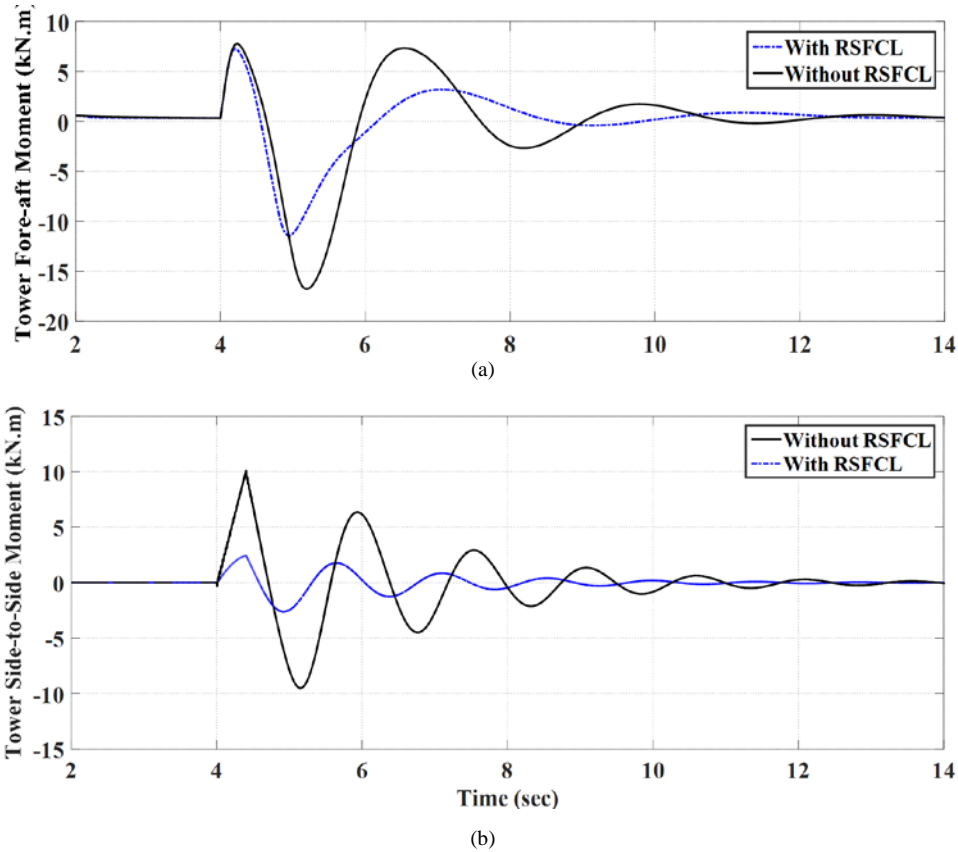


Fig. 17. Dynamic performance of the WT under the extreme load with and without the RSFCL. (a) Blade flapwise moment. (b) Blade edgewise moment.

During the fault, blade experiences moments in flapwise bending and edgewise bending in the blade root. Fig. 17(a) shows the average flapwise bending moment in the blade root. The axial wind force, gravity force and centrifugal force contributes the most to the flapwise bending moment in the blade root. However, the average value of the flapwise moment is almost zero in normal operating state of the WT. At the beginning of the fault, the rotor speed increases, therefore the contribution of centrifugal force in flapwise bending moment in the blade root also increases. As the failure clear quickly after 200 ms, the flapwise moment fluctuations in the blade root gradually smooth, because the contribution because the axial aerodynamic force on rotor becomes negligible. Fig. 17(b) shows the average edgewise bending moment in the blade root. The rotor torque also

causes edgewise moment in the blade root and its contribution is estimated by the average value of the edgewise moment. As can be seen, there are several fluctuation trends in the value of the edgewise moment. After clearing the fault, fluctuations trend to fade off fast in edgewise bending moment in the blade root due to the large stiffness in edgewise direction of the blade. In both figures, RSFCL can significantly dampen the oscillations of the flapwise moment and edgewise moment. The WT tower experiences fore-aft and side-to-side bending moment at the tower base, as shown in Fig. 18. Fore-aft bending moment is mainly due to rotor thrust loading. Tower motions happen due to the tower's dynamic interaction with rotor blades. Due to large fluctuations in axial aerodynamic force on rotor, the tower fore-aft moment also fluctuates.



378
379

380
381
382

Fig. 18. Dynamic performance of the WT under the extreme load with and without the RSFCL. (a) Tower fore-aft moment. (b) Tower side-to-side moment.

Once a fault happens in the system, the value of the tower fore-aft moment first increases and then decreases due to the inertia of the tower, as shown in Fig. 18(a). The tower fore-aft moment first decreases and then increases because of the inertia of tower. The tower fore-aft motion is unable to quickly dampen because the complete weight of the WT operates on the tower base. Fig. 18(b) shows the side-to-side bending moment in the tower base. The rotor torque that operates on the tower top through gearbox/generator support can lead to the side-to-side tower moment at the tower base. Because of the large inertia of tower, the tower shows fluctuations on the

389 value of the side-to-side moment after clearing the fault, as can be seen in Fig. 18(b).

390 The results indicate that the proposed RSFCL has significant effect for reducing the fluctuations on the, blade flapwise add
391 edgewise moments, pitch actuator force and yaw moments, and tower fore-aft and side-to-side moments. Therefore, RSFCL
392 can be a promising solution for wind turbine controller performance with respect to extreme loads happening to mechanical
393 and aerodynamic parts during the severe disturbances.

394 6. Optimal Scheme Performance

395 The obtained results in Section 5 for the proposed combinatorial 50-MW wind farm and RSFCL confirmed that further
396 improvements in dc-link smoothness, extreme load, and LVRT capability of a wind farm can be achieved by increasing the
397 SFCL resistance as much as possible. However, as stated in (14), the high-resistance SFCL means a substantial amount of
398 energy is dissipated in the form of heat, resulting damage on SFCL construction and cooling system. This large energy
399 dissipation would lengthen the recovery time of the RSFCL (transition from resistive state to superconducting state) after
400 clearing the fault. Also, as stated in Section 3.2, for overcoming the unbalance power between the generator and converter, the
401 active power output of the wind farm, P_{WPP} should be appropriately increased during the fault to diminish the fluctuations of
402 dc-link capacitor voltage. However, depending on the grid code, reactive power production has highest priority during the
403 fault, occupying some portion of the maximum capacity of apparent power, and leading reduction in P_{WPP} . Hence, there is a
404 tradeoff between three above mutually contradicting criteria, SFCL resistance, energy dissipation, and active power output of
405 the WPP in order to achieve an optimal design of combinatorial 50-MW wind farm and resistive SFCL.

406 For optimization purposes, this section implements multi-criteria decision making (MCDM) methodology based on analytical
407 hierarchy process (AHP) detailed in the authors' prior work [23]. One of the outstanding characteristics of the MCDM
408 technique is the creation of the Pareto optimality for simultaneous multiobjective optimization in which algorithm figures out
409 all the nondominated solutions on the Pareto front (optimality) at the end of the optimization run. AHP is established as
410 beneficial technique providing the promising solutions to the complicated decision-making problems with different criteria.
411 The proposed optimization model contains three predefined criteria and two constraints that are expressed as

$$\begin{aligned} & \text{Min} \left\{ \frac{1}{R_{SFCL}}, \frac{1}{P_{WPP}}, Q_{SC} \right\} \\ & \text{Subject to} \begin{cases} T_{SFCL}^{\max} - 423 < 0 \\ \text{point} (V_{\text{grid}}, \Delta t_{sc}) \text{ within Area } A \end{cases} \end{aligned}$$

412
413
414 (16)

415 Where, maximum SFCL appeared resistance, R_{SFCL} maximum active power output of the WPP, P_{WPP} and minimum energy
416 dissipation, Q_{sc} are desirable. The proposed system (combination of 50 MW WPP and RSFCL) should be designed in such a

way that the following criteria are satisfied: 1) $T_{SFCL}^{\max} < 432^\circ$ for safe solder melting; and 2) fulfill Danish grid code requirement including LVRT and reactive power support requirement.

Based on (11), any change in the dimensions of the superconducting wires as well as fault durations may affect fault current limiting performance of RSFCL, and consequently the optimum design of the proposed system. Therefore, in this optimization, variable parameters are superconducting wire volume (V_{sc}), superconducting wire cross section (A_{sc}) and duration of the fault (Δt_{sc}). The constraints of the selected variables for the optimization problem are shown in Appendix (Table 3).

Considerately, if each variable is changed in 10 steps, three variables would create $10^3 = 1000$ alternatives when utilized in the electrical simulation model. These cases (378) that exceed the predefined optimization constraints must be omitted from feasible options.

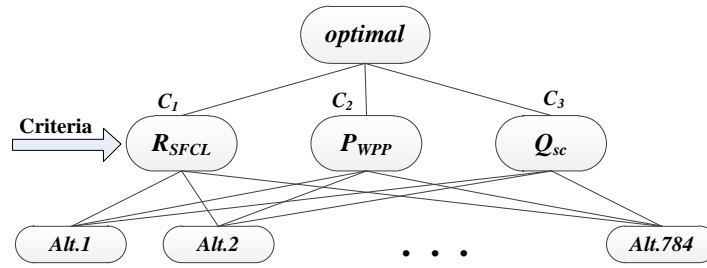


Fig. 16. Hierarchy process for optimal combinatory PMSG-based WT and RSFCL.

The goal of AHP method is to find a best case (desired solution) among the remnant number of 784 alternatives that can maximize each criterion satisfaction. Basically, for 784 alternatives (A_i , $i=1, 2, \dots, 784$) and 3 criteria (C_j , $j=1, 2, 3$), there are four steps considering decision problems by AHP as follows:

Step 1) Scrutinize the relation between objectives, criteria and alternatives to build the multi-layers hierarchical structure. Fig. 16 shows the multi-layers hierarchical structure for optimal combinatorial PMSG-based WT and RSFCL including optimal layer, criterion layer, and alternative layer.

Step 2) Compose a pairwise comparison matrix by assigning each alternative/criterion an optional number from 1/9 to 9. In this article, the three-point performance rating scale is defined for the importance of criteria, 9 (high), 5 (medium), and 1 (low). Based on the explanation in [23], if the importance of criteria C_1 , C_2 , C_3 are ranked as high ($C_1=9$), medium ($C_2=5$), and low ($C_3=1$), respectively, the criteria pairwise comparison matrix $C=[c]_{3 \times 3}$ can be expressed by

$$[C]_{3 \times 3} = \begin{matrix} & \begin{matrix} C_1 & C_2 & C_3 \end{matrix} \\ \begin{matrix} C_1 (R_{SFCL}) \\ C_2 (P_{WPP}) \\ C_3 (Q_{sc}) \end{matrix} & \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \end{matrix} = \begin{bmatrix} C_1 / C_1 & C_1 / C_2 & C_1 / C_3 \\ C_2 / C_1 & C_2 / C_1 & C_2 / C_3 \\ C_3 / C_1 & C_3 / C_2 & C_3 / C_3 \end{bmatrix} = \begin{bmatrix} 1 & 9/5 & 9 \\ 5/9 & 1 & 5 \\ 1/9 & 1/5 & 1 \end{bmatrix}$$

(17)

A similar method is applied to estimate the value of alternative pairwise comparison matrix $A_i=[a_{ij}]_{784 \times 784}$ ($i=1, 2, 3$) with

441 respect to each criterion.

442 Step 3) Compute the relative weight (priority) of the compared factor for the criterion according to the judgment matrix C
 443 and A . The criteria and alternatives weight vectors can be obtained by adding the array elements of each row of C and A matrix
 444 and then dividing by the sum of the element of columns. Here, the weight vector matrix of criteria w_{cj} ($j=1, 2, 3$) can be
 445 estimated by

$$446 \begin{bmatrix} w_{c1} \\ w_{c2} \\ w_{c3} \end{bmatrix} = \frac{1}{(1+9/5+9) + (5/9+1+5) + (1/9+1/5+1)} \begin{bmatrix} 1+(9/5)+9 \\ (5/9)+1+5 \\ (1/9)+(1/5)+1 \end{bmatrix} = \begin{bmatrix} 0.60 \\ 0.334 \\ 0.066 \end{bmatrix}$$

447 (18)

448 The analysis of the simulation results represents the degree of importance of alternative i in criterion j , i.e., d_{ij} , which is divided
 449 by its maximum value. This is followed by splitting the alternation range to 9 parts, allocating a proportional number from 1 to
 450 9 into each alternative a_{ij} as

$$451 a_{ij} = \text{Integer} \left(\frac{d_{ij}}{0.11 \text{Max}_i(d_{ij})} \right) \quad (19)$$

452 Since, a pairwise comparison matrix of the alternative A_i is compatible; it forms the calculation of the alternative weight vector
 453 simple via normalizing the elements of each column, reaching to wa_{ij} . These calculations can be formulated as

$$454 wa_{ij} = \frac{a_{ij}}{\sum_{i=1}^{784} a_{ij}} \quad (20)$$

455 The sum of the entire alternative weight vector with respect to the each criteria wa_{ij} and the criteria weight vector w_{cj} for $j=1, 2,$
 456 3 & $i=1, 2, \dots, 784$, forms a decision matrix (784×3) as

Alts.	<i>Criteria</i>		
	C_1 (w_{c1})	C_2 (w_{c2})	C_3 (w_{c3})
A_1	wa_{11}	wa_{12}	wa_{13}
A_2	wa_{21}	wa_{22}	wa_{23}
\vdots	\vdots	\vdots	\vdots
A_{784}	$wa_{(784)1}$	$wa_{(784)2}$	$wa_{(784)3}$

457
 458 Step 4) Calculate the best alternative, i.e., the highest priority value.

459 Usually, the criteria can be classified into the two opposite groups called the benefit and cost criteria [37]. A benefit criterion
 460 means that the better alternative has the higher grade. The inverse scenario is expressed true for the cost criteria. In this
 461 optimization study, the total energy dissipated is cost and the other criteria, i.e., the resistance of SFCL and power output of the
 462 PMSG, are benefit. Thus, the optimization problem can be summarized as a standard format for aggregating alternatives to

rank them based on the ratio performance approach detailed in [37], as given by

$$P_{AHP}^* = \max_i \left(\frac{(wa_{i1} \times w_{c1}) + (wa_{i2} \times w_{c2})}{wa_{i3} \times w_{c3}} \right) \quad \text{for } i = 1, 2, \dots, 784$$

(21)

For three levels criteria comparison, this weight vector must be calculated 25 times ($3^3 - 2$) by changing the importance of the criteria with respect to each other. The run results of the algorithm are shown in Table 4. As earlier mentioned, the Pareto optimality plays the significant role in choosing the best solution for optimization of all three criteria: resistance of SFCL, energy dissipation in SFCL, and active power output of the WT. However, for an approximate set of three-dimensional Pareto-optimal solutions, a search is performed for the tradeoff values between the optimums of the objective functions, using AHP, at the end of each optimization run, as shown in Fig. 17.

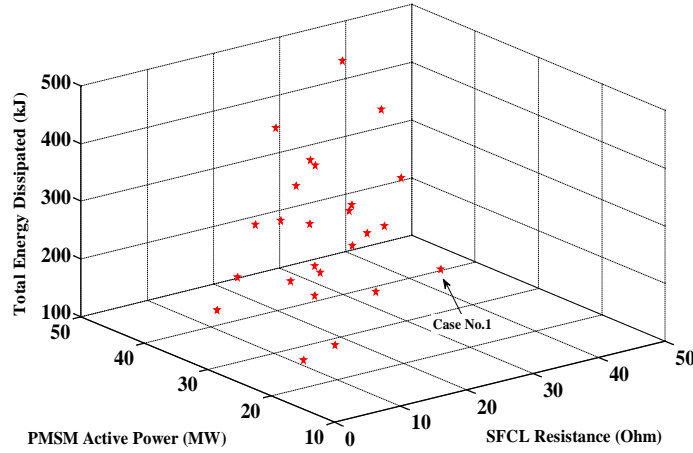


Fig. 17. Multi-objective optimization using AHP, Pareto front for three criteria.

The corresponding AHP optimization results are illustrated in Table 4. It is the tradeoff values between the 25 given set of mutually contradicting criteria. Referring to Table 4, if higher priority is given to the RSFCL, so case 9 (H-L-L) in which 26.15 Ω must be chosen. Similarly, for the power output of the PMSG-WPP or total energy dissipated priority selection, cases 20 and 24 (L-H-L and L-L-H) in which $P_{PMSG} = 28.59$ MW and $Q_{sc} = 128.92$ kJ must be selected, respectively. Moreover, the higher and lower active power delivered during the fault are obtained in case 1 (82.7 % of total capacity) and case 9 (32.7 %), respectively.

7. Conclusion

484 The paper proposes an effective approach using RSFCL as the additional support along with conventional converter control
 485 strategy based on the PI controller to further increase the rated active power of the installation, thereby enhancing dc-link
 486 voltage smoothness as well as the LVRT capability of the 50 MW WPP. Moreover, that was demonstrated that RSFCL can be
 487 a promising solution for improving wind turbine controller performance with respect to extreme loads on the wind turbine
 488 structure. With this approach, it is expected that the activation of the dc braking chopper and fast pitch angle control could be
 489 reduced in order to meet the international grid code requirements. An important feature of the proposed method is that a
 490 conventional PI control can be used, performing the reactive and reactive current injection, while the dc-link voltage never
 491 exceeds its safety limits. A further study is carried out to determine optimal performance of the combinatorial 50 MW PMSG-
 492 WPP and RSFCL. Therefore, the simultaneous and transformative approach based on the AHP method for the multiobjective
 493 optimization of embedded system has been introduced. A reconciliation between the three objecting functions, namely,
 494 resistive of SFCL, output power of PMSG, and energy dissipated in RSFCL has elicited by a 3-D alignment in the Pareto front
 495 having nondominated 25 solutions. However, a designer would be capable of selecting any of the solutions setting on the
 496 Pareto front without erratic problems on optimality.

497

498

499

Table 4. Achieved Optimal Alternatives Using AHP Method

Case No.	Priority	w_{c1}	w_{c2}	w_{c3}	$V_{sc} (m^3)$	$A_{sc} (m^2)$	$\Delta t_{sc} (s)$	$R_{SFCL} (\Omega)$	$P_{PMSG} (MW)$	$Q_{sc} (kJ)$
1	H-H-H	0.33	0.33	0.33	5.00E-04	9.20E-07	0.26	44.59	41.35	143.43
2	H-H-M	0.39	0.39	0.22	4.30E-04	1.04E-06	0.32	29.54	44.75	200.95
3	H-H-L	0.47	0.47	0.05	1.85E-04	1.04E-06	0.38	12.72	25.53	252.17
4	H-M-H	0.39	0.22	0.39	4.65E-04	1.04E-06	0.38	31.94	40.94	234.51
5	H-M-M	0.47	0.26	0.26	1.85E-04	9.20E-07	0.44	26.23	32.19	252.17
6	H-M-L	0.60	0.33	0.07	1.85E-04	1.04E-06	0.44	19.72	20.82	291.99
7	H-L-H	0.47	0.05	0.47	3.60E-04	9.20E-07	0.8	31.63	41.71	492.73
8	H-L-M	0.60	0.07	0.33	3.25E-04	9.20E-07	0.74	27.53	31.31	466.48
9	H-L-L	0.82	0.09	0.09	2.90E-04	1.28E-06	0.68	26.15	16.35	448.68
10	M-H-H	0.22	0.39	0.39	3.95E-04	9.20E-07	0.26	34.67	43.42	155.92
11	M-H-M	0.26	0.47	0.26	3.60E-04	1.04E-06	0.26	24.73	38.92	168.14
12	M-H-L	0.33	0.60	0.07	5.00E-04	1.40E-06	0.32	18.95	23.22	211.95
13	M-M-H	0.26	0.26	0.47	2.55E-04	1.04E-06	0.38	17.51	40.74	252.17
14	M-M-L	0.45	0.45	0.09	3.25E-04	1.52E-06	0.5	10.45	29.36	331.38
15	M-L-H	0.33	0.07	0.60	2.90E-04	1.16E-06	0.62	16.01	29.72	409.45
16	M-L-M	0.45	0.09	0.45	3.60E-04	1.52E-06	0.68	11.57	25.89	448.68
17	M-L-L	0.71	0.14	0.14	5.00E-04	1.88E-06	0.62	10.51	18.26	409.45
18	L-H-H	0.05	0.47	0.47	4.30E-04	1.76E-06	0.2	10.31	39.31	131.39
19	L-H-M	0.07	0.60	0.33	2.20E-04	1.64E-06	0.2	7.07	22.31	131.39
20	L-H-L	0.09	0.82	0.09	1.50E-04	1.16E-06	0.26	8.28	28.59	231.62
21	L-M-H	0.07	0.33	0.60	4.30E-04	1.88E-06	0.32	9.04	34.76	211.97
22	L-M-M	0.09	0.45	0.45	2.90E-04	1.64E-06	0.38	8.01	25.25	252.17
23	L-M-L	0.14	0.71	0.14	2.90E-04	1.76E-06	0.38	6.95	20.37	252.17
24	L-L-H	0.09	0.09	0.82	5.00E-04	1.88E-06	0.74	10.51	30.22	128.92
25	L-L-M	0.14	0.14	0.71	3.95E-04	1.76E-06	0.62	9.47	25.96	207.13

500

501 **Acknowledgement**

502 The authors would like to thank Ms. Bonnie Jonkman, the Senior Scientist of National Wind Technology Center (NWTC),
 503 National Renewable Energy Laboratory (NREL), for her critical and extensive support for using the FAST version 8.

504 **Appendix A**

505 See Table 1, Table 2 and Table 3.

506

507

Table. 1. Limits of Variables for Optimization Problem

Symbol	Quantity	Value
P_{rated}	Critical Temperature for HTS tape	15
T_0	liquid nitrogen temperature	77 °K
I_{c0}	Critical current	5 kA
C_p	Specific heat of HTS	3 MJm ⁻³ K ⁻¹
P_{cool}	Cooling power	700 kW
V_{SC}	HTS Volume	3e-4m ³
A_{SC}	HTS Cross section	1e-6m ²
R_{sh}	Shunt resistance of HTS	120 Ω
ρ_n	Normal resistivity	4e-8 Ωm
ρ_f	Flux flow resistivity	1e-9 Ωm

508

Table. 2. Parameters of the Proposed PMSG-WPP for Simulation

Symbol	Quantity	Value
Wind Turbine Parameters		
P_t	Rated turbine power	2 MW
v_{wind}	Rated wind speed	12 m/s
R	Blade radius	46 m
ρ	Air density	1.225
C_{p-opt}	Optimal power coefficient	0.45
λ_{opt}	Optimal tip speed ratio	8.32
PMSG Parameters		
P_{rated}	Rated generator power	2 MW
V_{rms}	Rated rms line-line voltage	0.69 kV
f	Rated frequency	60 Hz
ψ_r	Rated rotor flux	17 Wb
ω_m	Rated speed	1200
R_s	Stator winding resistance	0.015 pu
L_s	Stator winding inductance	0.057 pu
R_r	Rotor resistance	0.105 pu
L_{d, L_q}	d, q-axis synchronous inductance	8.75 mH
P	Number of Poles	6
H	Mechanical time constant	2.5 sec

509

510

Table. 3. Limits of Variables for Optimization Problem

Symbol	Quantity	Min Value	Step	Max Value
V_{SC}	Volume of HTS	5e-4m ³	5e-4m ³	1e-3m ³
A_{SC}	Cross section of HTS	1e-6m ²	5e-6m ²	1e-5m ²

Δt_{sc}	Duration of the fault	0 s	0.2 s	0.8 s
-----------------	-----------------------	-----	-------	-------

511 REFERENCES

- 512 1 Muyeen, S. M., Takahashi, R, Murata, T, Tamura, J.: ‘A variable speed wind turbine control strategy to meet wind
513 farm grid code requirements’, IEEE Trans. Power Syst., 2010, 25, (1), pp. 331-340.
- 514 2 A. Moghadasi, A. Sarwat, J. M. Guerreo, “A comprehensive review of low-voltage-ride-through methods for fixed-
515 speed wind power generators”, Renewable and Sustainable Energy Reviews, 2016, 55, pp.823-839.
- 516 3 Mohseni M, Islam SM., “Review of international grid codes for wind power integration: Diversity, technology and a
517 case for global standard. Renew. Sustain. Energy Rev., 2012; 16, (6), pp. 3876–3890.
- 518 4 A. Moghadasi, A. Islam, "Enhancing LVRT capability of FSIG wind turbine using current source UPQC based on
519 resistive SFCL," T&D Conference and Exposition, 2014 IEEE PES, 2014, pp. 14-17.
- 520 5 A. Moghadasi and A. Islam, “Enhancing LVRT capability of FSIG wind turbine using current source UPQC based on
521 resistive SFCL,” IET Gener. Transm. Distrib., 2014, 8, (3), pp. 563 – 572.
- 522 6 Z. Zhang; Y. Zhao; W. Qiao; L. Qu, "A discrete-time direct torque control for direct-drive PMSG-based wind energy
523 conversion systems," in Industry Applications, IEEE Transactions on, July-Aug. 2015, 51, (4), pp.3504-3514.
- 524 7 Ki-Hong K., Yoon J., Dong L., Heung, K.: ‘LVRT scheme of PMSG wind power systems based on feedback
525 linearization’, IEEE Trans, Power Electron., 2012, 27, (5), pp. 2376-2384.
- 526 8 Yaramasu, V., Bin Wu, Alepuz, S., *et al.*: ‘Predictive control for low-voltage ride-through enhancement of three-level-
527 boost and NPC-converter-based PMSG wind turbine’, IEEE Trans, Indust. Electron., 2014, 61, (12), pp. 6832-6843.
- 528 9 Farhadi M. and O. Mohammed O.: ‘Event based protection scheme for a multi-terminal hybrid dc power system,’ IEEE
529 Trans. Smart Grid, 2015, 6, (4), pp.1658–1669.
- 530 10 Yonghao G., Chunghun K., Chung C., "Nonlinear control for PMSG wind turbine via port-controlled Hamiltonian
531 system," in PowerTech, 2015 IEEE Eindhoven, July 2015, pp.1-6.
- 532 11 Mullane, A., Lightbody, G., Yacamini, R.: ‘Wind-turbine fault ride-through enhancement’, IEEE Trans, Power Syst.,
533 2005, 20, (4), pp.1929-1937.
- 534 12 Alepuz, S., Calle, A., Busquets, S., Kouro, S., Bin Wu.: ‘Use of stored energy in PMSG rotor inertia for low-voltage
535 ride-through in back-to-back NPC converter-based wind power systems’, IEEE Trans, Indust. Electron., 2013, 60, (5),
536 pp. 1787-1796.
- 537 13 Ibrahim, R.A., Hamad, M.S., Dessouky, Y.G., Williams, B.W.: ‘A novel topology for enhancing the Low Voltage Ride
538 through capability for grid connected wind turbine generators’, Energy Conversion Congress and Exposition (ECCE),
539 Raleigh, NC, Sept. 2012, pp.2389-2395.
- 540 14 Muyeen SM., Ali, MH., Murata, T., Tamura, J.: ‘Transient stability enhancement of wind generator by a new logical
541 pitch controller’, IEEE Trans. Power and Energy., 2006, 126, (8), pp. 742–752.
- 542 15 Amei, K., Takayasu, Y., Ohji, T., Sakui, M.: ‘A maximum power control of wind generator system using a permanent
543 magnet synchronous generator and a boost chopper circuit’, in Proc. Power Convers. Conf., Osaka, Japan, 2002,
544 pp.1447-1452.
- 545 16 Luo, F., Ma, D.S.: "Design of digital tri-mode adaptive output buck-boost power convertor for high efficient integrated
546 systems," IEEE Trans. Indust. Electron., 2010, 57, (6), pp.2151-2160.

- 17 Farhadi M. and O. Mohammed O.: 'Adaptive Energy Management in Redundant Hybrid DC Microgrid for Pulse Load Mitigation', IEEE Trans. Smart Grid, 2015, 6, (1), pp.54-62.
- 18 Farhadi M. and O. Mohammed O.: 'Performance enhancement of actively controlled hybrid DC microgrid and pulsed power load,' IEEE Trans. Ind. Appl., 2105, 51, (5), pp.3570–3578.
- 19 Deng, F., Chen , Z.: 'Low-voltage ride-through of variable speed wind turbines with permanent magnet synchronous generator', in Proc. IEEE IECON, Porto, Portugal, Nov. 2009, pp. 621–626.
- 20 Mullane, A., Lightbody, G., Yacamini, R.: 'Wind-turbine fault ride-through enhancement', IEEE Trans. Power Syst., 2005, 20, (4), pp. 1929–1937.
- 21 Matas, J., Castilla, M., *et al.*: 'Feedback linearization of direct-drive synchronous wind-turbines via a sliding mode approach', IEEE Trans. Power Electron., 2008, 23, (3), pp. 1093–1103.
- 22 Elshiekh. M.E., Mansour. D.A., Azmy A.M.: 'Improving Fault Ride-Through Capability of DFIG-Based Wind Turbine Using Superconducting Fault Current Limiter', IEEE Trans. Appl. Superconduct., 2013, 23, (3), pp. 1204-1208.
- 23 Ye, L., Lin, L.: 'Study of Superconducting Fault Current Limiters for System Integration of Wind Farms', IEEE Trans. Appl. Superconduct, 2010, 20, (3), pp.1233-1237.
- 24 Heydari, H., Moghadasi, A.H.: 'Optimization scheme in combinatorial UPQC and SFCL using normalized simulated annealing', IEEE Trans. Power Deliv., 2011, 26, (3), pp.1489-1498.
- 25 Kim, S.-Y., Kim, W.-W., Kim, J.-O.: 'Determining the location of superconducting fault current limiter considering distribution reliability', IET Gener. Transm. Distrib., 2012, 6, (3), p. 240-246.
- 26 Vahid Vahidinasab., 'Optimal distributed energy resources planning in a competitive electricity market: Multiobjective optimization and probabilistic design', Renewable Energy, 2015, 66, pp.345-363.
- 27 Moghadasi, A.H., Heydari, H., Farhadi, M.: 'Pareto optimality for the design of SMES solenoid coils verified by magnetic field analysis', IEEE Trans. Appl. Superconduct, 2011, 21, (1), pp.13-20.
- 28 Rosyadi, M., Mueen, S.M., Takahashi, R., Tamura, J.: 'Low voltage ride-through capability improvement of wind farms using variable speed permanent magnet wind generator', Electrical Machines and Systems (ICEMS), Beijing, china, Aug. 2011, pp.1,6, 20-23.
- 29 Jaramillo, F., Kenne, G., Lamnabhi, F.: 'A novel online training neural network-based algorithm for wind speed estimation and adaptive control of PMSG WT system for maximum power extraction', Renewable Energy, 2015, 86, pp.38-48.
- 30 Hosseini, S.H.; Farakhor, A.; Haghighian, S.K., "Novel algorithm of maximum power point tracking (MPPT) for variable speed PMSG wind generation systems through model predictive control," in Electrical and Electronics Engineering (ELECO), 8th International Conference on, 2013 , pp.243-247.
- 31 Adhikari, J.; Prasanna, I.V.; Panda, S.K., "Maximum power-point tracking of high altitude wind power generating system using optimal vector control technique," in Power Electronics and Drive Systems (PEDS), IEEE 11th International Conference on , 2015, pp.773-778.
- 32 Hunping, S., Nilles, J.L.: 'High-accuracy hysteretic current-mode regulator for powering microprocessors', Applied Power Electronics Conf. APE, Twenty-First Annual IEEE, March 2006, pp., 19-23.
- 33 Janowski, T., Kozak, S., *et al.*: 'Analysis of transformer type superconducting fault current limiters', IEEE Trans. Appl. Superconduct., 2007, 17, (2), pp. 1788–1790.

- 585 34 Gyore, A., Semperger, S., *et al.*: “Experimental analysis of different type HTS rings in fault current limiter,” IEEE
586 Trans. Appl. Superconduct., 2007, 17, (2), pp. 1899–1902.
- 587 35 Blair, S.M., Booth, C.D., Singh, N.K., Burt, G.M.: ‘Analysis of energy dissipation in resistive superconducting fault-
588 current limiters for optimal power system performance’, IEEE Trans. Appl. Superconduct, 2011, 21, (4), pp.3452,
589 3457.
- 590 36 S. Eckroad, ‘Superconducting Fault Current Limiters,’ Electrical Power Research Institute (EPRI), Technology Watch
591 2009.
- 592 37 Mulholland, J., Sheahen, T., Mcconnel, B., ‘Method for estimating future markets for high-temperature
593 superconducting power devices,’ IEEE Trans. Appl. Superconduct, 2002, 12, (2), pp.1784, 1789.
- 594 38 NREL, NWTC Information Portal, <https://nwtc.nrel.gov/FAST>.
- 595 39 Odgaard, P., Larsen, L., Wisniewski, R., Hovgaard, T.: ‘On using Pareto optimality to tune a linear model predictive
596 controller for wind turbines’, Renewable Energy, 2016, 87, pp.884-891.
- 597 40 Li, H., Yang, C., Hu, Y., Liao, X., Zeng, Z., Zhe, C.: ‘An improved reduced-order model of an electric pitch drive
598 system for wind turbine control system design and simulation’, Renewable Energy, 2016, 93, pp.188-200.
- 599 41 Heydari, H., Sharifi, R.: ‘Three-dimensional pareto-optimal design of inductive superconducting fault current
600 limiters’, IEEE Trans. Appl. Superconduct, 2010, 20, (5), pp.2301-2311.